12.75" Synthetic Aperture Sonar (SAS), High Resolution and Automatic Target Recognition[i]

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Abstract– The Autonomous Operations Future Naval Capability (AOFNC) program developed a 12.75" diameter autonomous underwater vehicle (AUV) and a Synthetic Aperture Sonar (SAS12) payload. This system falls under the lightweight designator of the Unmanned Undersea Vehicle (UUV) master plan. Bluefin Robotics Corporation and the Applied Research Laboratory of The Pennsylvania State University (ARL/PSU) developed the vehicle/payload system. In addition to the previous team members, Naval Surface Warfare Center Panama City (NSWC PC) developed the synthetic aperture image processing. The system will include motion compensation and beam formation software, real time data handlers, and automatic target recognition algorithms. NSWC PC provided test range services and test planning to the project, as well.

The AUV design is an open frame that allows modular payloads to be attached. The modules are self-contained and the surround is free-flooded. A plastic fairing covers the payload and vehicle subsystems. The payload power and communications are supplied through common interfaces. The vehicle hosts a suite of inertial, environmental, and heading sensors, as well as, a Doppler Velocity Log (DVL). Data from this sensor suite is combined to provide the information necessary for proper SAS operation. This data is used both in the SAS ping timing and ultimately in the correction of errors due to aperture misalignment. Vehicle and payload data and logs are recorded and used to evaluate system performance.

The SAS payload is designed using COTS data acquisition and communication hardware. The SAS operates at 180 kHz in the side looking mode. A suite of arbitrary waveforms can be transmitted to optimize SAS performance in a given environment. The broadband receiver is designed for minimal channel-to-channel gain and phase errors necessary for acquisition of high fidelity signals. Signals are filtered and decimated then passed to the recorder and processing systems. The individual element aperture determines the ultimate resolution limit. In principle, SAS12 can be processed for 25mm resolution at all ranges out to a maximum of 150 meters. One advantage of SAS is that the data collected can be processed to whatever resolution is defined by the user, within this limit. This is useful in resolution studies because the same data set can be processed for different resolutions. Typically real apertures have a fixed resolution proportional to the physical length. Depending on the real aperture system, this resolution may be constant or vary as a function of range.

The system will include real time automatic target recognition (ATR). The ATR consists of a set of algorithms developed by several different contributors. The master algorithm uses a rule based system to combine the information generated by the individual contributors. The result produces a lower false alarm rate that any single algorithm. The authors present performance for comparison to the existing data bases that relate ATR performance to image resolution. ATR performance is affected by clutter, bottom type, target aspect, and many other characteristics, as modified by the SAS resolution. Imagery is presented with ATR performance measures. Sonar performance is discussed in qualitative terms, and is based on image appearance and knowledge of what targets are present in the field. Quantitative performance measures are also presented in terms of requirements of the ATR, Probability of Detection (Pd), and Probability of False Alarm (Pfa).

I. Introduction

For AUV systems, where speeds are modest and the space for arrays is limited, SAS offers the potential to provide better resolution and area coverage rate than a comparable length real aperture sonar system. Improving the area rate per system is critical in reducing the number of systems needed to accomplish the same level of clearance. Reducing the system count to perform a particular job is beneficial from both, cost and logistic perspectives. In addition, because the resolution of a SAS can be made constant independently of frequency and range (via proper processing and within the bounds of the design), longer wavelengths can be used. The use of longer wavelengths (lower frequencies) without sacrificing resolution provides relatively small systems with detection and classification capabilities against buried targets. The potential for high performing underwater imaging systems of relatively small

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size is the primary motivation driving the development of SAS equipped AUV systems.

II. SAS Hardware Development

The SAS12 payload is a self-contained section that resides forward of the main vehicle electronics housing and battery section. A free-flooded nose is located forward of the SAS section. The vehicle is reconfigurable, so in some instances a high resolution forward-looking SONAR will be inserted into the vehicle nose section.

The SAS12 is designed to have a range of 150 meters for typical vehicle speeds of three to four knots. SAS is a constant area coverage rate system, in the current operational configuration. As the vehicle speed increases the range decreases. This relationship is shown in Figure 1. The bandwidth and apertures are set up to allow processing to 2.5 cm range and azimuthal resolution.
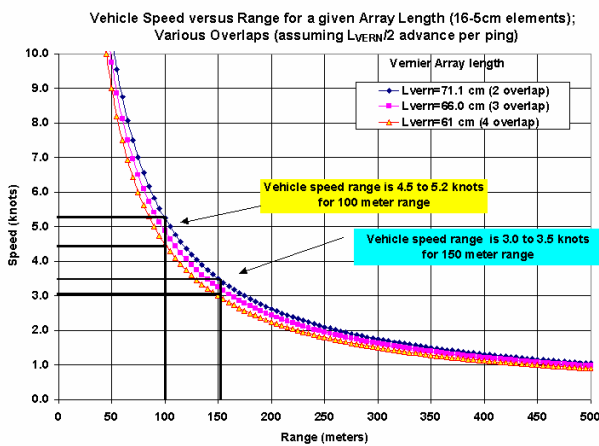

Figure 1. Range-Speed Envelope for SAS12

The SAS12 sub-system is comprised of two SONARs, one port and one starboard. Each SAS operates at a nominal frequency of 180 kHz. The outboard components consist of a projector and a 16-channel receiver. These transducers are designed to have a minimum of 30 kHz of bandwidth. A variety of Continuous Wave, Linear FM, and arbitrary waveforms are transmitted and processed. These outboard components are oriented in a side-looking configuration. The transmit and data acquisition components are separate for port and starboard. Currently, the raw SONAR data is merged with the navigation/attitude and recorded on a common disk drive. A SAS12 upgrade is in process that converts this system to one that processes the data in real-time and outputs a call list.

The SAS12 is packaged in a 24 cm diameter pressure vessel approximately 1.2 meters in length. The transducers are mounted beneath the pressure vessel. That entire package is mounted in a free-flooded ABS plastic fairing that is connected to the rest of the vehicle via joint bands. The SAS12 section is shown relative to the vehicle in Figure 2. High resolution imaging requires careful management of the gain and phase variance in the Data Acquisition System (DAS). To this end, the design and manufacturing tolerances of the transducers and associated

electronics have resulted remarkably low channel-to-channel variation. The SAS12 has relatively simple interfaces to the vehicle. The electrical interface consists of 28 V_{DC} power, serial communication, and Ethernet communication. Command, control, and status are passed between the vehicle and payload via TCP/IP protocol. SAS12 distributes all the conditioned power required for internal use. The vehicle passes position, attitude, and speed data to the payload for pulse timing and geo-location. Independent of the vehicle interface, SAS12 has additional wet connectors that allow shore power and communications without opening up the section. These can be used for maintenance, data off-load, and testing separate from the vehicle.
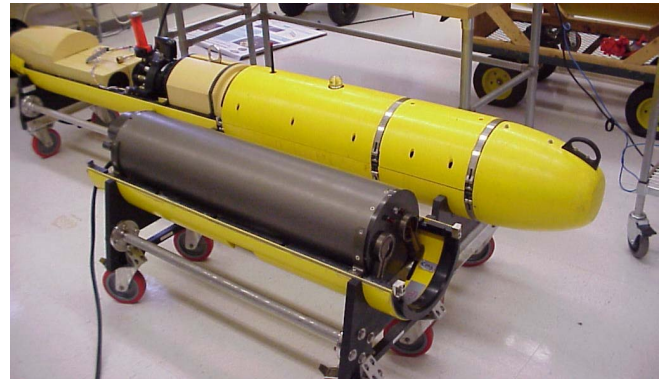

Figure 2: SAS12 with AOFNC 12 Vehicle

For clarity, Figure 3 depicts the solid model of the SAS12 subsystem with a translucent fairing. This view shows the location of the various components. The SAS12 is designed for neutral buoyancy.
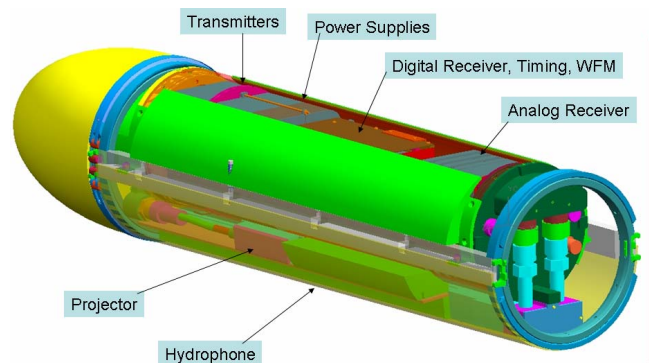

Figure 3: Solid Model of the SAS12 and ABS Fairing

SAS12 ping timing is tied to the advance rate of the vehicle. Nominally, the SAS12 advances 35.5 cm per ping. The Displace Phase Center (DPC) micro-navigation technique is used. As such, the SAS system is highly integrated with the inertial, speed of sound, and Doppler Velocity Log (DVL) sensors. This is required to provide the pulse timing algorithms with low-noise, high-fidelity, and low latency speed data. The SAS performance is highly dependent on this feature. The AOFNC vehicle originally had a 300 kHz DVL. The team worked with RD

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Instruments (RDI) to characterize the DVL performance as a function of frequency and altitude. Ultimately, a RDI 600 kHz DVL was selected as a compromise between short term speed accuracy and range requirements.

The SAS12 components, internal to the pressure vessel have been re-packaged to allow the addition of a real-time processing system. The motion compensation, beamforming, and automatic target recognition algorithms will be hosted on this hardware in late summer of 2006. This package consists of eight COTS processors and disk drives. The real-time sub-system has its own power conditioning components. Raw SONAR data is passed from the DAS to the Real-Time Processing (RTP) sub-system via 1000 baseT Ethernet. The configuration is shown in Figure 4. The system is designed for low-EMI emissions and efficient thermal management.
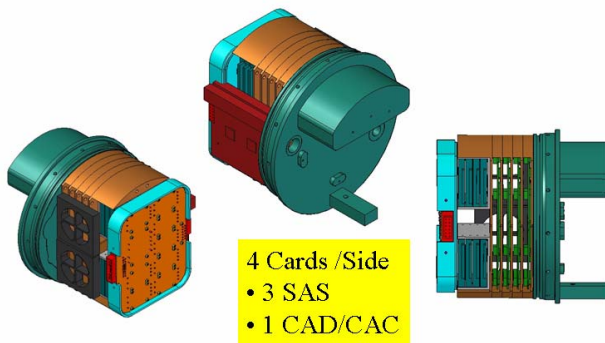

Figure 4. SAS12 Real-Time Processing Sub-System

Bluefin12 has a total energy capacity of 4.5 kWh to power the payload and all its subsystems. Bluefin12 is designed to cruise efficiently at 1.5 m/s, while being able to achieve a top speed of 2.5 m/s. The tailcone design is an evolution of the larger 21-inch design, where the motor, gearbox, propeller, and control surface all actuate in the horizontal and vertical directions. For communications, Bluefin12 has both, acoustic and RF modems. For tracking and emergency recovery, its subsystems include an acoustic beacon, a radio directional finder beacon, and high intensity flashing LED for localization during darkness. Bluefin12 navigation and positioning instrumentation includes a WAAS GPS receiver, an IMU, a digital compass and a RDI DVL. Mission planning, control commands and status monitoring of Bluefin12 are done with the topside control computer (a Pentium class computer) and associated software via shore cable, RF or acoustic modem communications. Figure 5 shows a Bluefin Robotics generated illustration of the SAS12/Bluefin12 system.
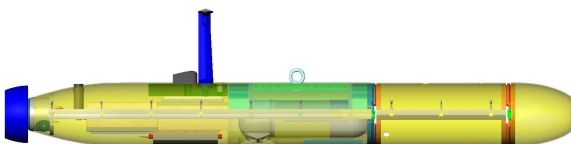

Figure 5: SAS12/Bluefin12 System.

III. Motion Estimation and Compensation

As with virtually all seagoing SAS systems, redundant phase centers are used to estimate the motion for SAS12. The basic algorithm is that used for other more mature systems, and it has been proven to reliably yield well-focused imagery [1]. In this scheme, the AUV's on-board navigation system supplies the array rotations, which are then subtracted from the time delays obtained using the RPC channels. Thus, the performance of the motion compensation is dependent on the quality of the AUV navigation data. This link is also found in the speed over ground estimate, which is used to control the ping timing. The accuracy requirements for the speed estimate scale with the physical array length.

Errors in the ping timing (or advance per ping, APP) will result in poor correlations on the RPC channels as well as nonuniform sampling of the synthetic aperture. This effect can be avoided somewhat by reducing the APP, which effectively shortens the portion of the array used for imaging. The cost of this workaround is reduced range coverage. The alternative is to use the RPC technique in a novel way to measure the APP error and subsequently correct the data. This approach has been documented in the literature by Oeschger [2].
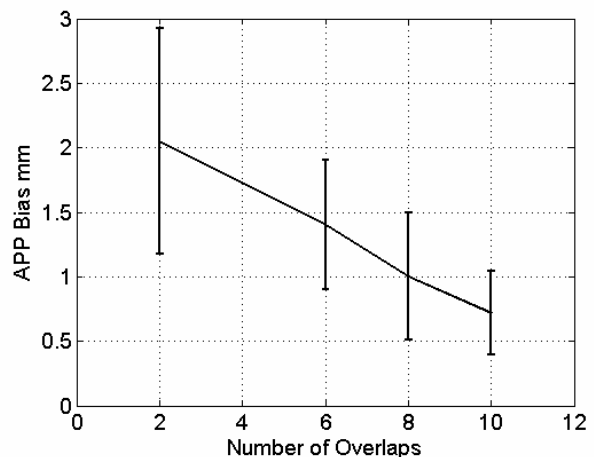

Figure 6. SAS12 Advance per ping bias as a function of number of overlapping channels.

The along track RPC technique was applied to SAS12 data having various numbers of overlapping RPC. The results shown Fig. 6 indicate the increasing APP bias as the number of overlaps decreases. This means the more time the vehicle has to integrate over, the greater the resulting bias and the less focused the final image will be.

IV. Automatic Detection Tests

During the engineering trials between May 2005 and March 2006, image quality steadily improved with system development. Figure 7 shows an image taken in the May 2005 sea test. The image quality at this time is such that the target is not recognizable.
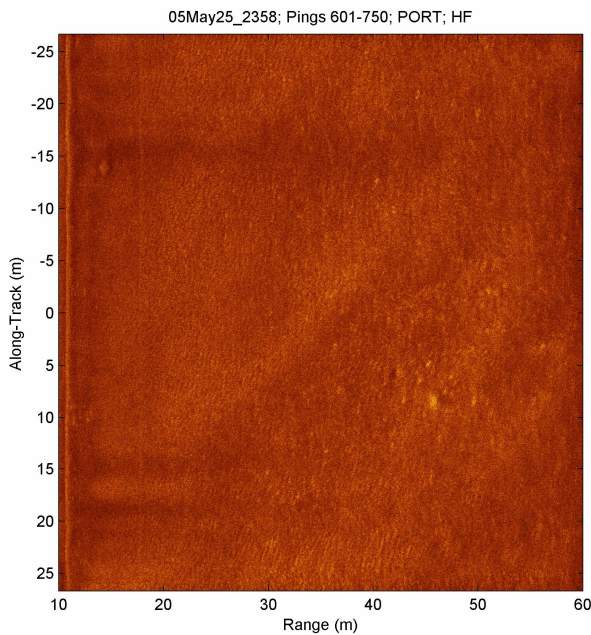
05May25_2358; Pings 601-750; PORT; HF

Figure 7: May 2005 Sea Test image with target at along track distance of +8 m, range 46 m.

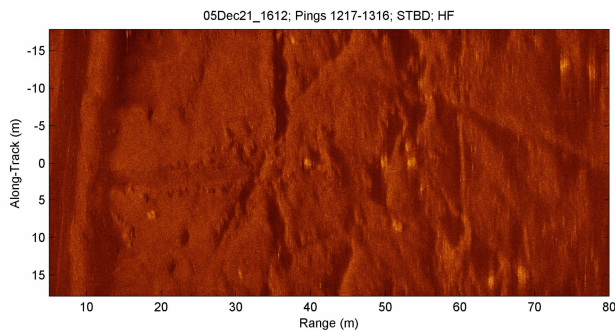05Dec21_1612; Pings 1217-1316; STBD; HF

Figure 8: December 2005 Sea Test image with numerous lobster and crab traps in the frame. Image quality is noticeably improved.

Figure 8 shows improvement in the resolution. The change is attributed to upgrade of the DVL from the 300 KHz model to the 600 KHz model, which reduced noise. This makes the forward progress between pings more accurately estimated. November and December 2005 tests were conducted in the Boston Harbor near Quincy, Massachussetts.

Figure 9 is beamformed from data acquired in a January 2006 sea test in the Gulf of Mexico, off Panama City, Florida. Another improvement is evident in the image clarity. This experiment shortened the distance between sonar transmissions by increasing the redundant phase center overlap from 2 to 10. The targets are about 70 cm in diameter.

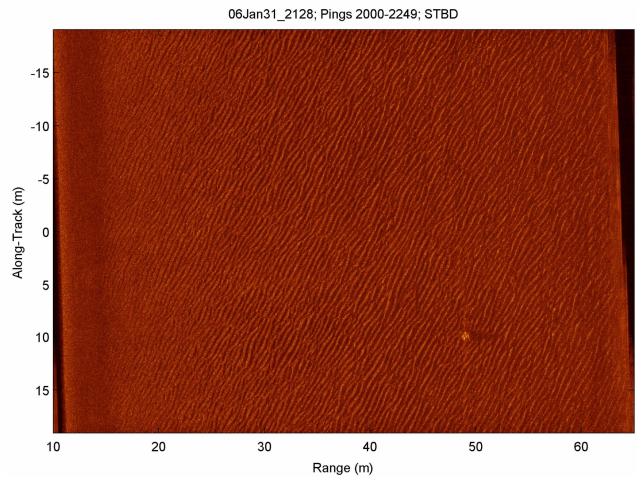06Jan31_2128; Pings 2000-2249; STBD

Figure 9: Results of the January 2006 sea test raised image quality to a useful level.

In March 2006, a sea test was completed in Panama City to produce a data base for training ATR. A coral field appears at the top of Figure 10 with a string of 6 targets extending below. The targets in this image are approximately 70 cm in diameter.

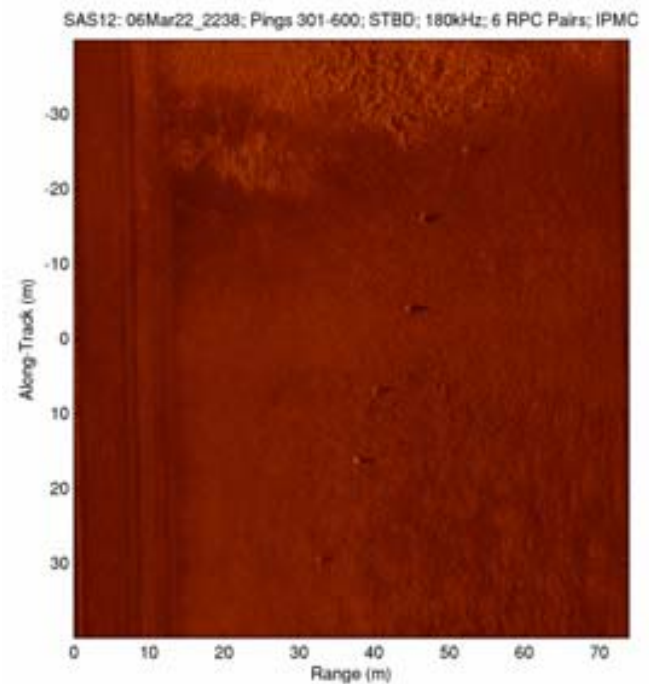SAS12: 06Mar22_2238; Pings 301-600; STBD; 180kHz; 6 RPC Pairs; IPMC

Figure 10: SAS12 image taken in the March 2006 sea test off Panama City, Fl.

An image quality measurement system (IQMS) was sought for the purpose of evaluating the sensor performance. A two dimensional matched filter was selected as the pattern recognition agent for its simplicity, robustness, and efficiency. This method did not employ spectral normalization and did not make any effort to manage false alarms. It would, therefore, not be a candidate for the ATR process in the fielded system. In this case, ATR is the sophisticated process that performs this function. IQMS merely informs the development group of the sensor system's fitness for presentation of the data to the ATR module.

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The March 2006 sea test was organized into some number of vehicle runs through a target rich environment. The targets were 60 to 150 cm along the major axis. The runs were grouped into categories A,B,C,D, and H. The A and C runs provided a set of images that were used for the matched filter kernels. The D and H data runs were used for test purposes. Run Pattern C is shown in Figure 11.

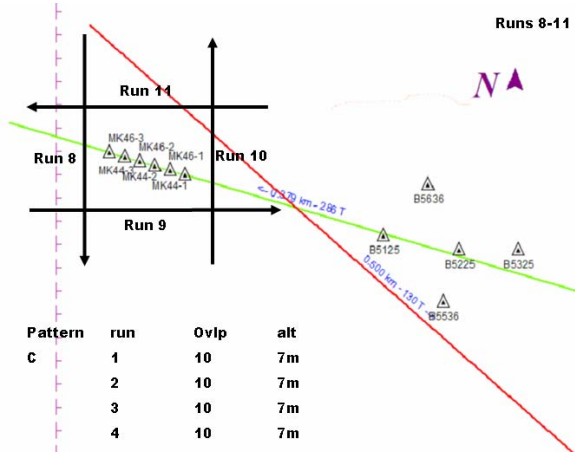| Pattern	run	Ovlp	alt
C	1	10	7m
	2	10	7m
	3	10	7m
	4	10	7m

Figure 11: Run Pattern C.

The six targets of primary interest were about 70-80 cm along the largest dimension. Targets at various ranges, drawn from the C run pattern, were used to form a sixteen sub-image array or library. These appear in Figure 12 after application of a window to each.
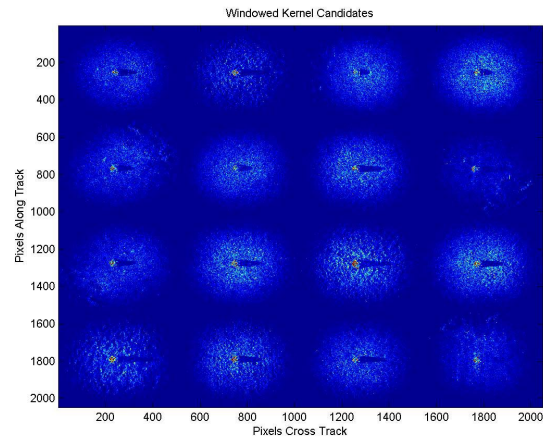

Figure 12: Image library from A and C run patterns.

Five highly responsive filter kernels were selected from the image library. These were transformed into a bank of matched filters [3] that were convolved with a number of images taken from the H run pattern group, illustrated in Figure 13.

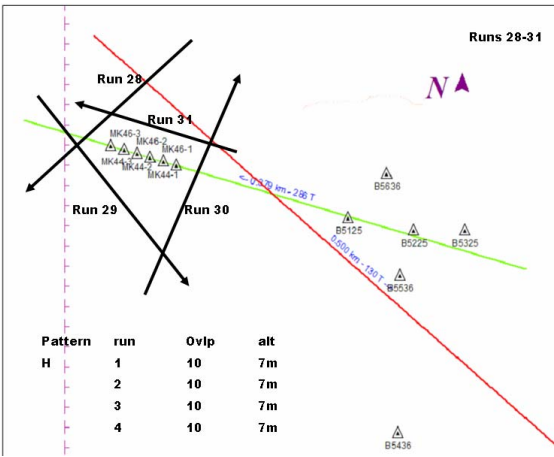| Pattern	run	Ovlp	alt
H	1	10	7m
	2	10	7m
	3	10	7m
	4	10	7m

Figure 13: Run Pattern H.

As the reader can see, the run directions in pattern H differ from those in pattern C. This will disorient the training backgrounds from the test backgrounds and alter the target aspects, so that the pattern recognition filters will not find aspect agreement with the test data. Any responses can then be attributed to aspect invariant similarities between the filter images and the test images. Statistical properties gleaned from the filter responses to known target locations and to known background locations can, therefore, be expected to indicate image fitness for examination by the ATR.

An image at the beamformer output is the input image to the ATR module. Let us refer to this image (from the IQMS perspective) as the input image. It was found that addition of the filter kernels for production of a single matched filter produced inferior results after convolution with the test data. Superior results were achieved with serial convolution of the five filters with the test data field, followed by addition of the magnitude filter output fields. This addition field was then smoothed by a 20 pixel by 30 pixel averaging operation to produce the recognition field. Examples of the input, output, and recognition fields appear in figures 14, 15, and 16, respectively.
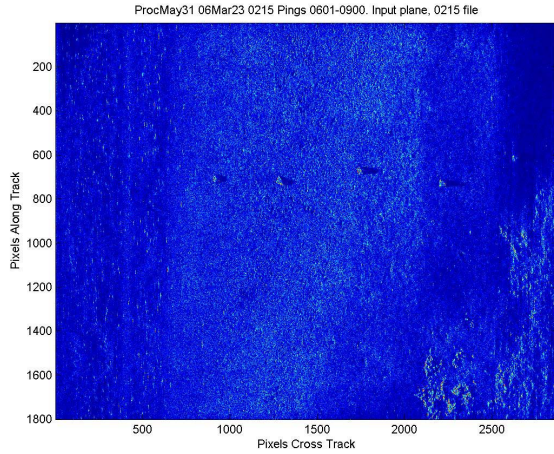
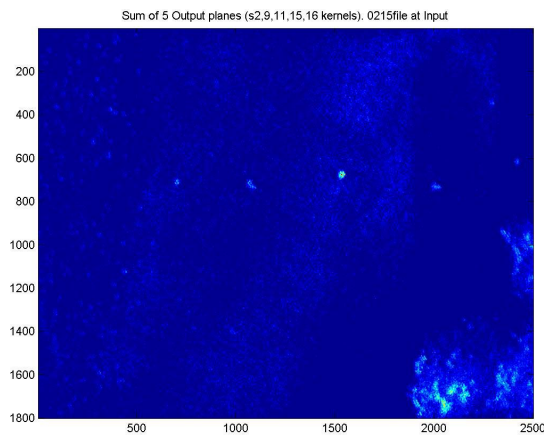Figure 14. Example of an input field (Magnitude).

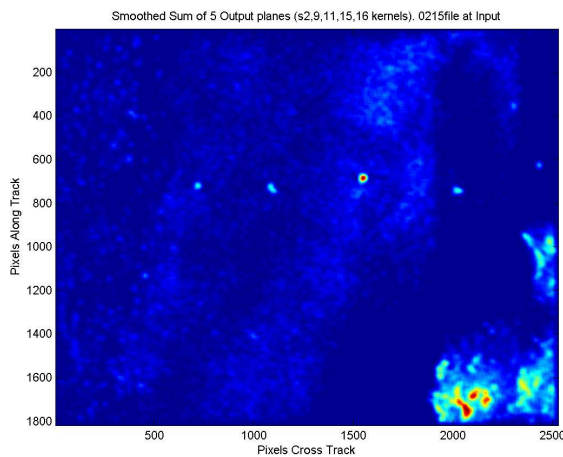

Figure 15: Output field example.

Figure 16: Recognition field example.

The recognition field is decomposed into two histograms. The first represents the peaks at the target locations. The second is made up of all values in regions of non-target, and for our purposes, the coral dominated regions were left out. A coral dominated region can be observed in the lower right hand corner of Figure 16.
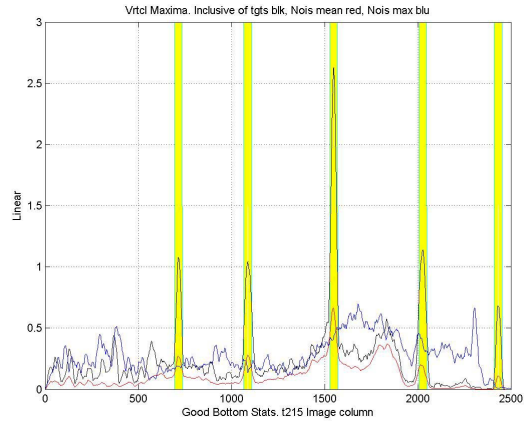

Figure 17: Linear profile of Recognition Field example image.

Figure 17 depicts the maxima in each column, over an along track selection that includes all targets, of the recognition image example (shown in Figure 15) in black. The yellow bars show the known target locations. Column-wise means appear in red and are somewhat influenced by the targets, but generally describe the background (noise) means. Column-wise noise maxima are shown in blue. The coral ridden areas were eliminated from the figure 17 noise maxima.

Five input images were processed. They held 23 recognizable targets. These histograms were converted to probability density functions (PDFs), and the PDFs converted to Probability Distributions (PDs). The probabilities of detection (Pd) and false alarm (Pfa) were formed by subtracting the two distribution functions from 1.0. The formula for Pd is:

$$Pd(n) = 1.0 - \int_0^n PDF(t \arg et)$$

The formula for Pfa is:

$$Pfa(n) = 1.0 - \int_0^n PDF(background)$$

Where n is the threshold value.

Logs of Pd and Pfa are graphed vs. threshold value in Figure 18. These are graphed in black and red, respectively. The difference between them is representative of the log likelihood ratio (LLR) [4], which appears in blue. Notice the point in Figure 18 where all targets are above threshold and the probability of false alarm is minimized. Because ATR seeks to preserve all actual targets at every stage of its cascade, the value of the LLR, at this threshold is of particular interest. The LLR at this threshold is the single value metric chosen to characterize image quality for this project. This selection ties the combination of hardware

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response, noise immunity, beamformer, and motion compensation competence to an expectation of ATR performance.
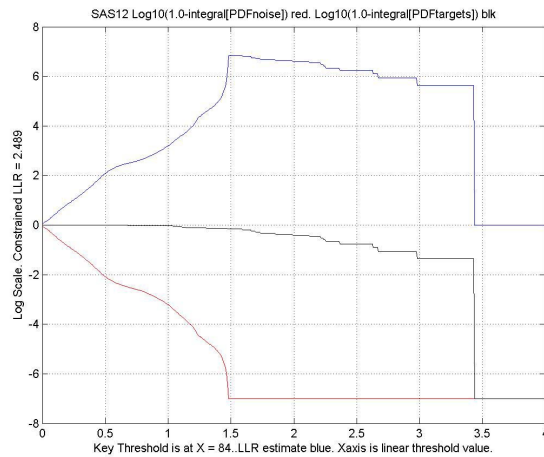

Figure 18: Log Pd, Log Pfa, and LLR for the five SAS12 images considered.

Notice that, for this example, involving 23 targets from 5 image frames, the key threshold where Pd departs one, is at a value of 84, where a value of 500 corresponds with an abscissa value of 4.0. This means the threshold value of interest on the figure 18 x axis is 84 times 4 divided by 500. An artificial limit of 10^{-7} was set on the probabilities. This made the graph readable.

Fewer than 30 target examples reduces the statistical confidence. In this case the confidence level is in the neighborhood of 75%.

V. CONCLUSION

SAS12 is a sensor payload developed for high resolution in a compact package for Autonomous Operations Future Naval Capabilities (AOFNC). The autonomy depends on an independent recognition capability, that depends, in turn, on sonar fidelity. SAS fidelity depends strongly on accurate estimation of APP. An image quality measurement system (IQMS) was developed and applied to SAS12 data. The purpose was to offer a tool to the project engineer for assistance in grading sonar performance. Although simple inspection would lead an observer to the conclusion that these images improved over the past year and have attained high quality, a quantification method that measured sonar performance in ATR terms was needed. IQMS provides a quick field test for numerical grading of current sonar image quality. The SAS12 image quality for this exercise was determined to be 2.489. This is the LLR at the smoothed summed two-dimensional matched filter bank output, at the threshold set just below the lowest target peak.

ACKNOWLEDGMENTS

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